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# Applied Computational Fluid Dynamics in Support of Aircraft/Store Compatibility and Weapons Integration – 2007 Edition

1Lt. Judson Babcock
*US Air Force SEEK EAGLE Office (AFSEO), Eglin AFB, FL*
judson.babcock@eglin.af.mil

## Abstract

*The Air Force SEEK EAGLE Office (AFSEO), Eglin AFB, FL, is the United States Air Force (USAF) authority for weapons certification efforts. AFSEO performs test and evaluation for aircraft/store compatibility certification. Computational fluid dynamics (CFD) is employed to support this process. Determining the flow about an aircraft/store combination can be extremely difficult. Complicated geometry features such as pylons, launchers, grid fins, and internal weapons bays create severe aerothermodynamic and acoustic environments which are challenging to numerically simulate. Rapidly and accurately modeling the trajectory of store separation in a high-volume simulation environment presents an additional challenge. The USAF requirement for numerous, simultaneous and quick-reaction solutions for a wide variety of stores and aircraft can only be accomplished through application of parallel high performance computing resources that meet the significant computational and memory demands associated with the certification computational environment.*

*Before operational use, all aircraft/store configurations must be certified for safe loading, carriage and jettison/release. AFSEO provides flight certification recommendations which are based on combinations of engineering analysis, ground, and flight testing. Engineering analyses is provided by disciplines in carriage loads, store separations, flutter, ballistics, stability and control, and electromagnetic compatibility, and interference. The AFSEO Computational Aeromechanics Team provides time-critical CFD support for engineering analyses to optimize ground and flight testing. This contribution takes the form of carriage aerodynamic loads, store separation predictions, and visualized flow field physics. The knowledge created reduces risk, lowers cost, and speeds the fielding of new weapons. This paper discusses six of the most recently applied AFSEO CFD tasks related to specific aircraft/store investigations and certifications.*

## 1. Introduction

The AFSEO establishes ground test requirements, performs engineering analyses, develops flight test profiles, and directs real-time flight tests to support the aircraft and store certification process*. To provide this capability, AFSEO maintains a core of engineering expertise in the areas of aircraft and store loads, store separations, vibration and flutter, stability and control (S&C), ballistics, and electromagnetic compatibility and interference. As aircraft and weapon systems have become more complex, certification costs have risen due to the historical dependence on expensive and time-consuming ground and flight testing. USAF funding available to acquire weapon systems has been significantly reduced in recent years, effectively limiting the resources available to perform store certification. Consequently, AFSEO has placed increased emphasis on modeling and simulation (M&S) tools to supplement current ground test methods and to optimize flight test programs.

Because the simulation tools employed by the engineering disciplines are dependant on the availability of accurate aerodynamic data, AFSEO employs CFD to supplement wind tunnel results in the engineering analyses. For numerous USAF fixed-wing aircraft carrying sophisticated weapon systems, AFSEO CFD routinely provides the capability for calculating carriage aerodynamic loads (point and/or distributed), predicting store separation trajectories, generating aerodynamic databases, and determining S&C handling characteristics deltas. It also provides a design capability via the validation of S&C systems and the analysis of unsteady aerodynamic loading on component and control surfaces.

AFSEO's primary tool is the CFD code, Beggar. Beggar has a unique, user-friendly grid assembly process

* "Stores" include almost anything attached to the aircraft wings or fuselage including bombs, missiles, fuel tanks, sensor pods (navigating, targeting, sensing), pylons, ejector racks, and rail launchers.

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that utilizes the latest developments in overset grid technology. In Beggar, the flow solver is tightly coupled with a multiple degree-of-freedom (6+DOF) algorithm. This provides a time-accurate store separation prediction capability that includes modeling of control surface deployments and deflections. A large history of wind tunnel and flight test data comparisons has repeatedly validated this CFD capability.

Quick-reaction projects do not typically provide sufficient time for wind tunnel or extensive flight testing. Such projects now often rely on CFD to provide rapid, accurate M&S. Beggar provides a parallel computing capability for rapid turn-around to support test and evaluation and operations. However, in its response to quick-reaction projects, the AFSEO CFD team is sometimes slowed by a limited availability of computing resources; high-performance computing (HPC) resources are critical to the CFD team's mission.

## 2. Problems and Methodology

Two primary challenges for CFD in the AFSEO production environment include the requirement for rapid response to immediate warfighter needs and the ability to provide accurate aerodynamic data to mitigate risk in testing throughout the acquisition cycle. As HPC capabilities have expanded and solver functionality and efficiency have improved, customer expectations have risen with respect to both of these aspects. CFD problem sets have consequently grown both in frequency and complexity. The AFSEO CFD code, Beggar, is equipped to handle these challenges.

Beggar employs an automated Chimera (overlapping) assembly scheme to provide the capability for addressing the complex geometries encountered in AFSEO certification efforts. The equations of fluid motion are solved time accurately using a cell-centered, finite volume, implicit, upwind Roe numerical scheme with limiters, coupled with a Newton relaxation method for the time-accurate sub-iterations. Currently available turbulence models include Baldwin-Lomax (most validated), Baldwin-Barth, k-ε with wall functions, Spalart-Allmaras (S-A), Detached-Eddy Simulation (DES), and a combined S-A/DES.

Three numerical tasks are performed at each iteration: grid blanking and interpolation between overlapping grids to allow communication between blocks; computation of inviscid and/or viscous flow solution; and solution of the equations of rigid-body motion for the store. Beggar's 6+DOF provides for fixed and/or moving control surface capabilities including closed-loop feedback control, internal resistance for moving components (applied spring force, viscous damping torque, or friction) such as deflecting canards, deploying fins, range-extending wings, fixed pivot-point, and porous boundary conditions. References 1–4 give further details of and validation cases for the Beggar code.

## 3. Results

This paper presents results from project tasks completed in FY 2007, specifically, a jettison analysis of the Small Diameter Bomb (SDB) from the F-16, a free-stream analysis of the SDB, wake analysis of the Massive Ordnance Penetrator with deployed grid fins, flow field analysis of the BQM-167, A-10 Hellfire separation analysis, and grid data compilation for B-52H Miniature Air Launched Decoy (MALD) separation performed in lieu of wind tunnel analysis. While the AFSEO CFD team completed many other tasks in FY07, these are representative of the team's, design, production, validation, and quick-reaction M&S capabilities.

### 3.1. F-16 SDB Jettison Studies

The SBD, designated GBU-39/B, contains a 250 pound warhead, measures 6 feet in length, is guided by GPS and inertial sensing, with an approximate range of 44 miles. This problem showcases the ability to numerically model a store with complex geometry, in this case folded wings and wing braces over the body (Figure 1). Because of the complicated nature of modeling the wings, braces, and the SDB body, this computational model contains 11 million cells. The BRU-61 suspension system is used to carry up to four SDBs on the F-16 (Figure 2). The BRU-61 model contains another 2 million cells.

In order to certify the BRU-61/SDB for safe flight on the F-16, configuration and flight condition limitations were necessary. Because of time constraints, wind tunnel testing could not be completed prior to this initial flight testing. Instead, CFD was used to simulate the jettisons of the BRU-61/SDB off the F-16 while varying ejection forces to determine safe and unsafe configurations.

Taking advantage of the numerous HPC resources available to the CFD team, AFSEO completed 33 trajectories of the BRU-61 with varying SDB configurations that resulted in problem sizes from 15 million to 30 million. The jettison results were completed and allowed the AFSEO Separations team to make a recommendation for a safe flight test envelope, allowing initial flight testing to proceed. These results also allowed the Separations team to refine the wind tunnel test plan around those points that were potentially hazardous, thus increasing test efficiency and reducing cost.

The results of this analysis demonstrate the capability of CFD to accurately predict complication suspension and store separation from a parent F-16 aircraft in support of flight test missions. By using CFD on the available HPC assets, valuable time and money were saved prior to flight testing.

### 3.2. SDB Freestream

Part of the larger F-16/SDB certification effort is a comprehensive freestream study on the SDB itself. This study is being done in accordance with the wind tunnel analysis and the data is being used to compare against the wind tunnel data. Much refinement was done on the SDB computational model as part of this study, which resulted in the current 11 million cell model.

The freestream run matrix that was done in support of the model refinement consisted of 800+ computational points spread over several different Mach numbers and a range of pitch and yaw orientations. A variety of comparisions were also made between available CFD solvers and different levels of grid refinement. The best level of grid and solver accuracy from this study led into the final freestream analysis, which consisted of 840 runs of varying Mach numbers and store orientations. These parameters were the same as the wind tunnel points, allowing a direct comparison between the CFD solutions and the wind tunnel.

The results of this analysis demonstrate the capability of CFD to accurately predict the aerodynamic characteristics of a complicated store in flight.

### 3.3. Massive Ordnance Penetrator Analysis

The Defense Threat Reduction Agency has funded a technology demonstration to develop a large scale penetrator. The Massive Ordnance Penetrator (MOP), a 30,000 pound class penetrator, is being developed to more effectively defeat deeply buried, hardened facilities. The Computational Aeromechanics Team was tasked to produce free-stream, grid, and wake analysis data to aid in the MOP's development.

CFD was initially used to predict aerodynamic forces and moments on the MOP in free-stream. The data gathered was compared with wind tunnel force and moment coefficients to provide a basis for model validation. Having matched the wind tunnel data, a suite of grid points and a time-accurate trajectory simulation was requested using the B-52 as the platform for release. A sample pressure plot is shown in Figure 3 of the MOP just below the bay of the B-52.

Further analysis was requested to study the wake produced by the MOP with the grid fins at various attitudes. A detailed model of the grid fin was developed for analysis. A completed model of the MOP with detailed grid fins is shown in Figure 4. With all four grid fins on the MOP, this problem exceeded 100 million points (as compared to the B-52/MOP configuration with simplified fins using ~30 million points). This posed challenges as unconventional grid building techniques were used in order to keep the number of points down. At the time of this paper, the wake analysis had not been completed.

### 3.4. BQM-167

The use of CFD to identify the External Pitching Moment on the BQM-167 due to engine exhaust impinging the Rocket Assisted Take Off (RATO) body was extremely successful[5]. The desired RATO angle setting was calculated from these predicted forces and moments, which ensured successful launch of the target drone. The success of this project led directly to requests for further analyses of the drone that included safe separation of the RATO at RATO burn out, and alternative suspension hardware to improve RATO separation[6].

The current work for the drone is now focused on identifying the aerodynamic forces and moments of the drone during the launch phase. This launch phase extends from the RATO ignition with the engine operating at 95% revolutions per minute (time =0.0) through the RATO separation (time = 5 seconds). A large part of the work is to model two different rails to see the impact to aerodynamic forces and moments for the first .5 seconds of launch (Figures 5 and 6). A run matrix of about 800 grid points has been identified for each rail in order to determine the forces and moments on the drone.

One of the rails has been modeled and preliminary runs have been made with the engine on. These show that an asymmetrical flow occurs over the empennage and RATO body due to the asymmetrical shape of the rail. A thrust diverter is located on the left side while a RATO support apparatus is located on the right side. It was found that a side force will be present on the RATO causing a nose right during the initial .5 seconds of launch. A sample plot of pressure contours is provided in Figure 7. Since this yawing moment is caused by a net side force on the RATO body, a rolling moment will also be imparted to the drone during launch. This initial analysis includes only the engine on. Further analysis will include turning the RATO on and seeing the effects on the aero forces and moments over the first .5 seconds of launch. A similar analysis will also be done for the other rail which is more symmetrical in its geometry. This CFD analysis is made possible by the HPC resources available to the Computational Aeromechanics Team.

### 3.5. A-10 Hellfire Separation Analysis

M&S was required as part of the process to certify the AGM-114N Hellfire II for deployment from the A-10

Warthog (Figure 8). Part of this process is to predict the jettison characteristics of the AGM-114N Hellfire II and LAU-145 launcher combination, which required a spectrum of free stream, flowfield, jettison, and grid analyses.

The AGM-114N Hellfire II computational model was developed from supplied CAD geometry, resulting in a 8 million cell model. Along with the newly-built viscous A-10 model, computational runs for this analyses reached sizes on the order of 50 million cells. Free stream analyses were completed on the Hellfire, the LAU-145 Launcher, and the LAU-145/Hellfire combination. Jettison trajectories and grid runs were done for the LAU-145/Hellfire combination as well as the LAU-145 by itself. In total, 293 computational points were produced to complete these requirements.

This analysis showed that at the given flight conditions, a safe jettison of the LAU-145 launcher and AGM-144N Hellfire II is possible. This result, made possible by HPC resources, led to the issuance of the initial flight clearance for the A-10/Hellfire II.

### 3.6. B-52 MALD Numerical Wind Tunnel Sims

The AFSEO Store Separations and CFD teams work together to enhance modeling and simulation (M&S) capability to support flight testing and better arm the warfighter. A notable example of this is the developmental weapon program for the MALD is shown in Figure 9. A 4% scale model of the B-52 was originally slated for wind tunnel testing. When coupled with a 4% model of the MALD with its complex grid fin Stability Augmentation Device, it became apparent to both the MALD and B-52 Program Office (PO) that such testing would not render credible data. Based on the AFSEO CFD team's validated B-52 model and experience with MALD design and separation issues gained during earlier F-16 support efforts, CFD was a logical choice for generating the necessary grid data in lieu of wind tunnel testing.

AFSEO and the B-52 PO agreed on a data set consisting of 13 carriage solutions, 20 separation trajectories, and 6,992 runs to generate aerodynamic grid data for AFSEO separation analyses. This data set is based on a combination of 2 angles-of attack, 2 Mach numbers, 4 sideslip angles, 4 pitch angles, 3 roll angles, and 92 static positions beneath the B-52 (simulations representative of wind tunnel testing grid data). The B-52 Heavy Stores Adapter Beam is designed to carry as many as 8 MALDs. To reduce the total numeric grid point count, the CFD team generated a reduced-point MALD containing only 3.5 million cells (13 million fewer cells). This dummy MALD made the size of the problem more manageable, on the order of 50 million vice 140 million cells. Figure 10 shows CFD-predicted pressure contours for a typical carriage configuration.

The CFD team normally provides 10s to 100s of CFD solutions or data points for support projects. The MALD request represents an order of magnitude increase in requirement. To accomplish this objective, the AFSEO CFD team developed case management software for automated job submission, maintenance and cleanup of CFD executables and resultant data files. The team successfully validated and employed this automation software on AFSEO's in-house Dedicated High Performance Computing Investment asset; however, internal resources were not sufficient for the production scope of the MALD analysis. To overcome the significant shortfall, the CFD team has employed the case management software on HPC assets at Army Research Laboratory (ARL) (Zornig) and Engineer Research and Development Center (ERDC) (Sapphire). HPC support in making these assets available to work this project has made an unrealistic M&S suspense realizable.

This large run matrix was started in FY 06, with the last 1,000 runs being completed in FY 07. This project has shown that M&S (CFD specifically) has the ability to virtually replace wind tunnel testing where needed and where appropriate by providing a comparable amount of data in a comparable or shorter amount of time. This capability provides the advantage of reducing risk and cost while maintaining schedule for critical acquisition programs[†].

## 4. Significance to DoD

This project increases combat capability for the current fleet of tactical and strategic aircraft with associated weapon systems. AFSEO provides flight certification recommendations that are based on a combination of engineering analysis, ground, and flight testing. The AFSEO CFD team provides time-critical support for engineering analyses that is used to optimize the application of ground and flight testing, thus reducing risk and lowering the cost of fielding new weapons.

The AFSEO CFD team enhances combat capability for the DoD by reducing the cost and schedule associated with wind tunnel and flight tests, by eliminating inherent limitations associated with current ground test techniques, by reducing risk associated with flight testing in developmental weapon programs, and by cultivating development and validation of the next generation of weapon systems. Improved CFD capabilities are promoting quicker reaction to immediate warfighter needs, as demonstrated by the SDB and A-10 Hellfire tasks discussed in this paper.

[†] Typical wind tunnel testing for aircraft-weapon compatibility has a 6- to 12-month lead time and costs from $500K to several $M.

Currently, the AFSEO library of numeric models includes 13 fixed-wing aircraft and more than 33 weapon systems, sensors, and smart store interfaces. Plans for improvements to our existing grid library include further additions to the B-2 geometry, creation of a viscous F-16 model with deflecting control surfaces (nearing completion), future addition F/A-22 and several unmanned platforms, and model refinements for several JSF variants. Increasing the number of aircraft and weapon platforms in the library equates to a greater capability for the CFD team to respond to quick-reaction tasks, which in turn can reduce the fielding time for the operational use of weapon systems.

## 5. Systems Used

HPC resources are crucial to successful execution of AFSEO CFD responsibilities. The CFD team has relied on Challenge allocations at ARL (Linux Network Cluster), Space and Missile Command (SGI Origin 3000), ERDC (SGI Origin 3900, Cray XT-3), Jaws (Linux Network Cluster), and on internal AFSEO computing resources. AFSEO's Penguin 64-bit Opteron (20 x 16 GB RAM plus 440 × 8 GB RAM); 4 × 28-CPU IBM NetFinity Blade with 2 GB RAM per processor; 64-CPU IBM Linux Cluster; and networked Linux dual-processor desktop machines. Challenge status and High Performance Computing Modernization Program (HPCMP)-funded hardware has significantly alleviated the strain on AFSEO's resources and have allowed a two-fold increase in productivity over FY 05 as noted in Table 1.

**Table 1. AFSEO CFD Computer Usage**

| FY | No. Solns | Avg. No. CPUs | Total CPU-Hours | Avg. Points *(millions)* | Avg. RAM *(GB)* |
|---|---|---|---|---|---|
| 01 | 112 | 20 | 215K | 3.9 | 5.0 |
| 02 | 226 | 24 | 511K | 5.4 | 6.1 |
| 03 | 337 | 24 | 741K | 7.5 | 8.0 |
| 04 | 540 | 30 | 1.45M | 15.0 | 12.0 |
| 05 | 845 | 30 | 1.87M | 23.2 | 14.7 |
| 06 | 4607 | 42 | 3.45M | 34.7 | 46.0 |
| 07* | 4703 | 45 | 3.65M | 40 | 50.0 |

*As of 1 Jun 07

For the class of computationally intensive problems now being experienced, AFSEO front-end processing can require up to 8 GB RAM per processor, as demonstrated with the B-52/MALD investigation, while back-end processing typically requires 1 to 4 GB per processor. File storage requirements have grown accordingly. Table 2 summarizes computing statistics on the tasks described in this paper.

**Table 2. AFSEO CFD Task Statistics**

| Task | Avg. No. CPUs | Max RAM *(GB)* | Max Storage *(GB)* |
|---|---|---|---|
| F-16/SDB | 64 | 12 | >2,000 |
| BMQ-167 | 28 | 5 | ~500 |
| A-10 Hellfire | 28 | 8 | ~800 |
| MOP | 128 | 64 | >5,000 |
| B-52/MALD | 64 | 50 | >3,000 |

## 6. Concluding Remarks

The growing list of complex tasks within this Challenge project is showing no sign of reaching a plateau. HPC support for the AFSEO mission is even more important than in prior years. Our continued success in supporting the warfighter relies heavily on the availability of significant HPCMP resources available for AFSEO use. This includes both challenge status allocations at the MSRCs as well as dedicated hardware.

High-performance computing resources play a vital role in the AFSEO process of granting flight test clearances and aircraft/store certification recommendations. As applications increasingly exhibit greater complexity and require both heightened accuracy and faster response, computing resources must keep pace by providing sufficient numbers of processors, computing speed, memory, data transfer rates, and availability. As the HPC community meets these continually expanding needs, the CFD community in general and the AFSEO CFD team specifically will be able to continue providing maximum combat capability to the warfighter.

## Computational Technology Areas

Computational Fluid Dynamics

## References

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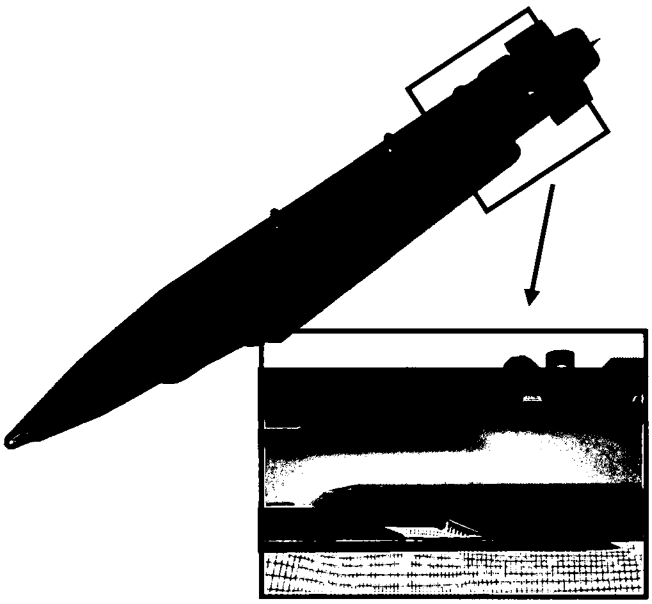

**Figure 1. GBU-39/B small diameter bomb computational model**

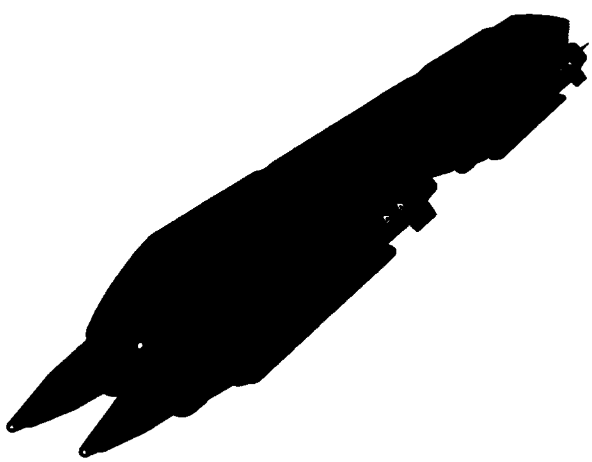

**Figure 2. BRU-61/SDB sample configuration**

**Figure 3. B-52/MOP**

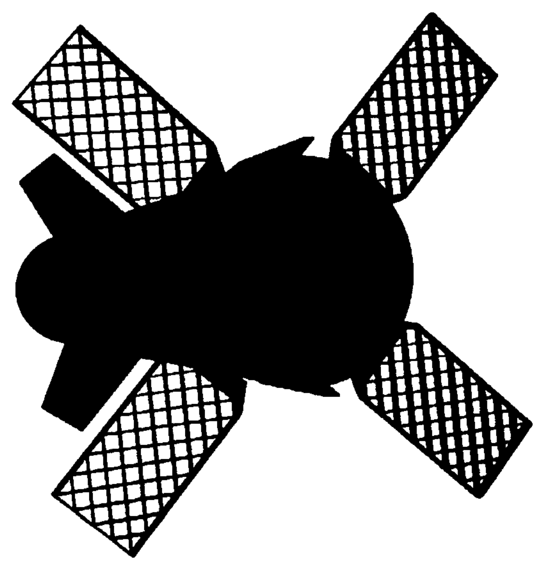

**Figure 4. MOP with grid fins**

**Figure 5. BQM-167 Rail #1**

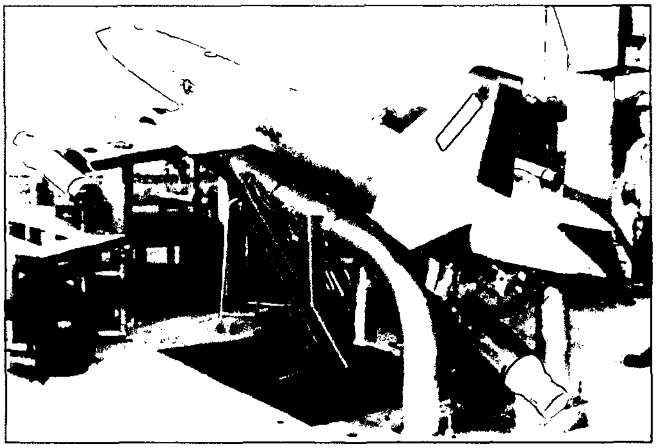

Figure 6. BQM-167 Rail #2

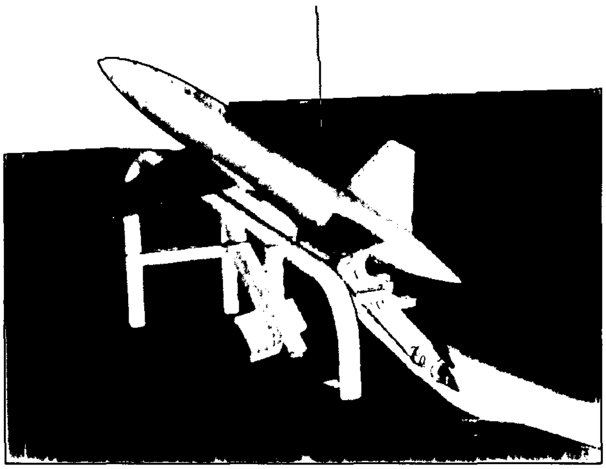

Figure 7. RATO pressure contours

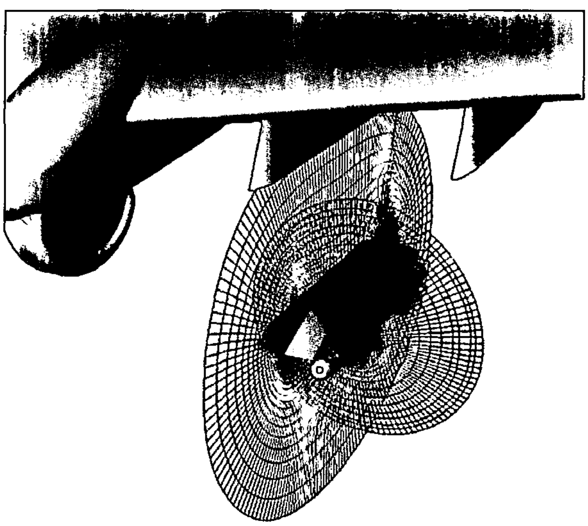

Figure 8. A-10/LAU-145/AGM-114N hellfire grid system

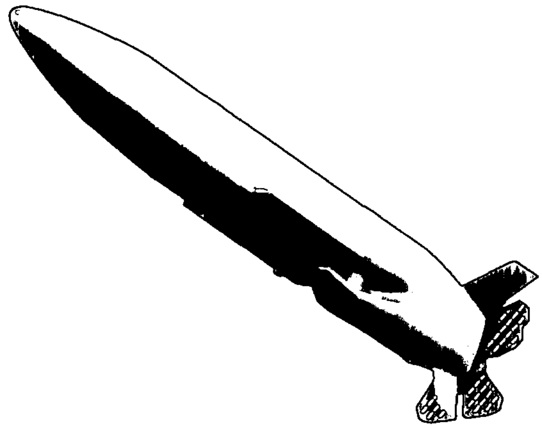

Figure 9. Miniature air launched decoy

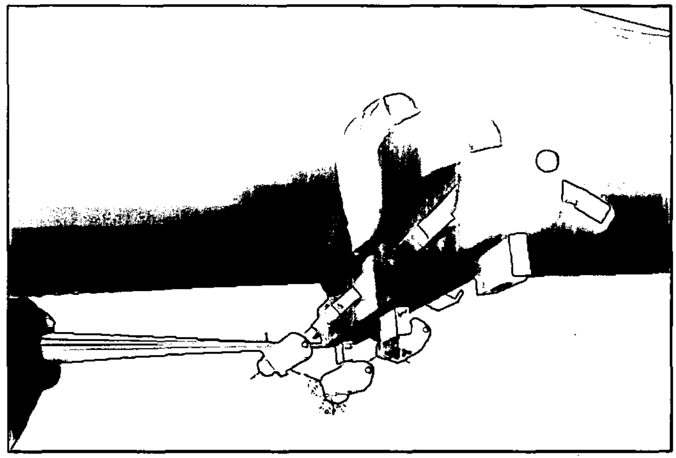

Figure 10. MALD/B-52 heavy stores adapter beam configuration